

Coherent photon scattering background in sub-GeV/ c^2 direct dark matter searches

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Proposed dark matter detectors with eV-scale sensitivities will detect a large background of atomic (nuclear) recoils from coherent photon scattering. This background climbs steeply below ~ 10 eV, far exceeding the declining rate of low-energy Compton recoils. The upcoming generation of dark matter detectors will not be limited by this background, but further development of eV-scale and sub-eV detectors will require the use of low- Z target materials, such as helium, to avoid a large rate of coherent photon scattering, or highly efficient methods to reject photons when they scatter.

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Interest in sub-GeV/ c^2 mass thermal relic dark matter models has inspired ideas for direct detection experiments with eV-scale [1–3] and sub-eV [4–6] thresholds [7]. For such light dark matter, the recoil energy differential scattering rate is restricted to energies below the detection thresholds of direct detection experiments motivated by weak-scale and supersymmetric models [8, 9].

Radiation may scatter coherently or incoherently from atoms and nuclei. Backgrounds from incoherent elastic recoils of MeV-scale electrically neutral penetrating radiation limit the reach of high-mass dark matter search experiments. The rate of these incoherent scattering backgrounds in the region of interest for low-mass dark matter searches is small, and has been considered less important than non-radiation backgrounds [7]. Notably, Compton scattering from photons is suppressed at energies below the binding energy of atomic electrons. In contrast, the coherent scattering of neutral particles, such as coherent neutrino scattering [10] or coherent dark matter scattering, produces an enhanced spectrum of low-energy recoils. Coherent photon scattering across an atom produces a low-energy background spectrum that may overwhelm low threshold dark matter detectors.

A photon with energy $E_\gamma = cp_\gamma \approx 1$ MeV scattering at angle $0 \leq \theta \leq \pi$ from an atom with mass $M \approx 10$ GeV/ c^2 , will transfer a small momentum q and recoil energy E_r .

$$E_r = \frac{q^2}{2M} = \frac{(2p_\gamma \sin \frac{1}{2}\theta)^2}{2M} \quad (1)$$

$$\lesssim \frac{(2 \cdot 10^6 \text{ eV}/c)^2}{2 \cdot 10^{10} \text{ eV}/c^2} = 200 \text{ eV}$$

The differential coherent scattering cross section is also strongly suppressed when coherence is lost for $q > \hbar/a_B = 3.7$ keV/ c , where a_B is the Bohr radius. This small energy deposition can be safely ignored for most applications, but not for upcoming dark matter searches.

The angle differential cross section for coherent photon scattering and its effects on photon transport have been well studied [11][18]. The dominant Rayleigh scattering cross section can be defined in terms of atomic

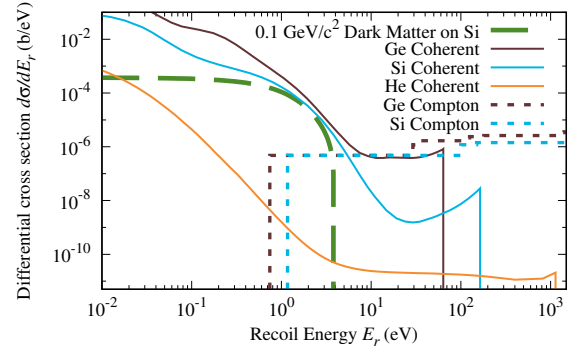


Figure 1. Energy differential cross sections for 1460 keV photons from ^{40}K decay in free silicon, germanium, and helium atoms. The low energy portion of the coherent scattering spectrum is dominated by Rayleigh scattering, while the high energy components are dominated by nuclear Thomson scattering and Delbrück scattering [11, 12]. The high energy cutoff of the coherent spectra vary with mass and photon energy as per Equation 1. The Compton scattering spectra shown is an approximation using the Klein-Nishina formula, with cutoffs for the electron shell binding energies and the semiconductor bandgaps [13–15]. All energies are given in true recoil energy. The spectral shape expected in silicon for the elastic scattering of dark matter with 0.1 GeV/ c^2 mass is shown assuming a Maxwellian dark matter velocity distribution with $v_o = 220$ m/s, $v_{esc} = 544$ m/s, and $v_e = 244$ m/s [16].

form factors $F(q, Z)$ multiplying the non-relativistic spin-averaged Thomson scattering cross section σ_T from a single electron with mass m_e :

$$\frac{d\sigma_T}{d\Omega} = \frac{e^4}{2m_e^2 c^4} (1 + \cos^2 \theta) \quad (2)$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_T}{d\Omega} F(q, Z)^2 \quad (3)$$

where Z is the atomic number and Ω is the solid angle. Additional contributions to the scattering amplitude from nuclear Thomson scattering, nuclear resonance scattering, and Delbrück scattering are important at large momentum transfers [12]. By a change of variables, the

Recoil Energy Range [eV]	Integrated Scattering Rate [recoils (kg.yr) ⁻¹]		
	Ge	Si	He
<0.01	72	16	1.0
0.01–0.1	34	13	0.5
0.1–1	16	5	0.012
1–10	0.8	0.9	6×10^{-5}
>10	0.10	0.012	0.0010

Table I. Expected free atom coherent photon scattering rates in a low-background experiment with a 0.04 counts/kg/day background from low-energy Compton scatter recoils of 1461 keV ⁴⁰K decay photons. This Compton scattering background rate has been demonstrated by the IGEX experiment [17], and is typical of kg-scale dark matter experiments. The ratio of the coherent background rate to the low-energy Compton background rate is approximately independent of the photon energy except above the kinetic cutoff energy given by Equation 1. At low recoil energies $\lesssim 0.02$ eV, coherent photon and dark matter scattering rates for atoms in condensed systems will differ from the scattering rates for free atoms (see text).

energy differential cross section is

$$\frac{d\sigma}{dE_r} = \frac{d\sigma}{d\Omega} \frac{2\pi M c^2}{E_\gamma^2} \quad (4)$$

Detailed scattering-matrix calculations that accurately calculate all contributions to coherent photon scattering are available for free neutral atoms with $Z \geq 13$ and have been validated by many experiments [19]. Figure 1 shows the scattering-matrix calculated cross sections for silicon and germanium; relativistic form factors [20] with anomalous scattering corrections [21] are used to approximate the cross section for helium.

Within crystals, coherence of photon scattering between atoms introduces structure factors that determine whether photons scatter from a single atom or the whole crystal. The scattering intensity off the entire crystal I compared to the total scattered intensity I_o is given by the Debye-Waller factor [13]. This factor may be written as,

$$\frac{I}{I_o} = \exp\left(-\frac{q^2}{2M} \frac{\langle U \rangle}{\langle U_o \rangle^2}\right) \quad (5)$$

where $\langle U \rangle$ is the average kinetic energy per lattice site of the crystal, $\langle U_o \rangle \sim 0.02$ eV is the average zero point energy per lattice site, and $q^2/2M$ is the recoil energy when scattering from a single atom. Even at zero temperature where $\langle U \rangle = \langle U_o \rangle$, scattering off the entire crystal is exponentially suppressed for recoil energies greater than the zero point energy. Other emergent effects in condensed matter that can be exploited for dark matter detection, such as multiphonon scattering [6], will also occur with photons at these low recoil energies.

While the cross sections for only 1461 keV photons are shown in Figure 1, the ratio of coherent-to-Compton scattering rates can be used to approximate the behaviour of the entire spectrum of background photons in dark matter experiments. The ratio of Rayleigh, nuclear Thomson, and electron Thomson (non-relativistic Compton) scattering differential cross-sections is fixed within a factor of $1 \leq 1 + \cos^2 \theta \leq 2$ for any given nuclear target and recoil energy below the kinetic cutoff given in Equation 1.

Figure 1 shows that the differential rate of coherent photon scattering in high- Z materials below recoil energies of 10 eV far exceeds the expected rate from Compton scattering. Upcoming experiments sensitive to GeV/ c^2 -scale dark matter will not be limited by this Raleigh scattering background as their thresholds are ≥ 35 eVnr[1, 3]. Higher energy recoils from nuclear Thomson and Delbrück scattering would be observable if nuclear recoils from coherent photon scattering can be discriminated from electron recoils from Compton scattering and beta decays. SuperCDMS SNOLAB would need to exceeds its goals for electron recoil / nuclear recoil discrimination to observe these higher energy components of coherent photon scattering.

Expected coherent photon scattering rates for kg-scale dark matter experiments are shown in Table I. Sub-eV germanium, silicon [3, 4], or aluminum [5] experiments with large exposures may use high-efficiency active vetoes to reduce both the low-energy Compton scattering and coherent scattering rates background below the low rates achieved by IGEX using passive shielding [17]. Detectors using helium [2, 6] or other low- Z targets will largely avoid the coherent photon scattering background.

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